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Performance of the meteorological radiation model during the solar eclipse of 29 March 2006

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Abstract

Various solar broadband models have been developed in the last half of the 20th century. The driving demand has been the estimation of available solar energy at different locations on earth for various applications. The motivation for such developments, though, has been the ample lack of solar radiation measurements at global scale. Therefore, the main goal of such codes was to generate artificial solar radiation series or calculate the availability of solar energy at a place.

One of the broadband models to be developed in the late 80's was the Meteorological Radiation Model (MRM). The main advantage of MRM over other similar models was its simplicity in acquiring and using the necessary input data, i.e., air temperature, relative humidity, barometric pressure and sunshine duration from any of the many meteorological stations.

The present study describes briefly the various steps (versions) of MRM and in greater detail the latest version 5. To show the flexibility and great performance of the MRM, a harsh test of the code under the (almost total) solar eclipse conditions of 29 March 2006 over Athens was performed and comparison of its results with real measurements was made. From this hard comparison it is shown that the MRM can simulate solar radiation during a solar eclipse event as effectively as on a typical day. The value of this comparison is further enhanced if it said that the sky was cloudy almost all the duration of the solar eclipse event.

1 Introduction

The demand of exact knowledge about the availability of solar energy at different locations on the earth's surface has been increasing recently because of its use as one of the most promising renewable energy sources. Solar data, on the other hand, are nowadays used in diverse disciplines, including climatology, micro-meteorology, biology, agriculture, glaciology, urban planning, architecture, mechanical and environ-

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

mental engineering. The design of many solar conversion devices, such as thermal appliances, requires the knowledge of solar radiation availability on horizontal as well as sloped surfaces. Also, the estimation of solar radiation on inclined surfaces starts with the determination of the corresponding values on horizontal plane.

It is well known that the number of the existing solar radiation stations is not adequately large throughout the world, in order to provide the required data for mapping solar radiation at a global scale. On the other hand, long-term solar radiation measurements are needed by scientists and solar energy system designers for various applications, such that the development of Solar Radiation Atlases and the generation of Typical Meteorological Years (TMYs) are nowadays important tasks. Nevertheless, because of an ample lack of such data worldwide, most of the above applications must primarily rely on simulation techniques. For instance, the US National Solar Radiation Data Base provides hourly radiation data and TMYs for 239 US sites, but 93% of these data come from appropriate modeling (Maxwell, 1998; Maxwell et al., 1991).

In the context of the above, various solar radiation models (mostly broadband) have started being developed since the middle of the 20th century to calculate solar radiation components on a horizontal surface, under clear-sky conditions mostly. The performance of a number of broadband models tested against theoretical and measured data under clear-sky conditions has been presented by Gueymard (1993a, 2003).

The Atmospheric Research Team (ART) at the National Observatory of Athens (NOA) has developed the so-called Meteorological Radiation Model, or MRM in brevity (Kambezidis and Papanikolaou, 1989, 1990a; Kambezidis et al., 1993a, 1997). The initiative of this development was to derive solar radiation data for places where these are not available because of lack of such measurements. To do that, the MRM employed meteorological data only (viz. air temperature, relative humidity, barometric pressure and sunshine duration) that are available worldwide.

The MRM code passed through different phases of development since its first version. Its latest version is 5. The original form of MRM (MRM v1) worked efficiently under clear-sky conditions, but it could not work under partly-cloudy or overcast skies. MRM

ACPD
7, 12807–12843, 2007

B. E. Psiloglou and H. D. Kambezidis

EGU

v2 introduced new analytical transmittance equations and, therefore, became more efficient than its predecessor. Nevertheless, this version still worked well under clear-sky conditions only. These deficiencies were resolved via the development of MRM v3, derived by T. Muneer's research group at Napier University, Edinburgh (Muneer et al., 1996, 1997, 1998; Muneer, 1997;) after successful co-operation between ART and his group. MRM v3 was included in the book edited by Muneer (1997). Through the EC JOULE III project on *Climatic Synthetic Time Series for the Mediterranean Belt* (acronym: CliMed), a further development of the MRM was achieved, which is referred to as version four (MRM v4), providing further improvement in relation with the partly-cloudy and overcast skies. The algorithm of MRM v4 was used by Prof. Hassid, Technion University, Israel, to make simulations and comparison with Israeli solar radiation data (unpublished work). In using the code, he found some errors mainly in the calculation of the daily solar course in the sky; these errors were later incorporated in the algorithm. On the other hand, Gueymard (2003), in an inter-comparison study employing various broadband models, used MRM v4 and found it not to be performing well in relation to others. These tests forced ART to reconsider the source code of MRM. The effort resulted in discovering further errors in the transmittance and solar geometry functions; new transmittance and more effective solar geometry functions were, therefore, introduced from the international literature concluding to MRM v5. Also the recent solar constant of 1366.1 $Wm^{-2}$was incorporated in version 5. A full description of the code is given in Sect. 2.

MRM has successfully been used by the *Chartered Institution of Building-Service Engineers* (CIBSE) of UK under the *Solar Data Task Group* in 1994 (Muneer, 1997). Apart from that specific task, MRM can be used in a variety of applications, among of which the most important nowadays are:

1. estimating solar irradiance on horizontal plane to be used as input parameter to codes calculating solar irradiance on inclined surfaces with arbitrary orientation,

2. estimating solar irradiance on horizontal plane with the use of available meteoro-

logical data to derive the solar climatology at a location,

3. filling gaps of missing solar radiation values in a series of historic observations from corresponding observations of available meteorological parameters,

4. providing results for engineering purposes, e.g., solar-energy applications, PV efficiency, energy-efficient buildings and daylight applications.

The primary objective of this study is to test the performance of the new version of MRM during the recent solar eclipse of 29 March 2006. The simulation of solar radiation levels by a broadband model during an eclipse event is, therefore, made for the first time in the international literature because of the difficulty to describe correctly the atmospheric conditions and solar geometry during the phase of the eclipse within the code. The results of this study have, however, a scientific and not a practical value, but can justify the performance of MRM v5 under very "adverse conditions" as those of a solar eclipse. The sun's disk coverage during the eclipse maximum on 29 March 2006 was 84% at NOA's solar radiation station featuring an almost total eclipse. For comparison, the performance of the model is also tested during the preceding day of the eclipse, i.e., 28 March 2006.

2 Model description

MRM is a broadband algorithm for simulation and estimation of solar irradiance on horizontal surface, using widely available meteorological information, viz. values of air temperature, relative humidity, barometric pressure, and sunshine duration as input parameters. This section provides a detailed description of the newly developed MRM, version 5, incorporating all recent knowledge on the subject.

2.1 Clear-sky MRM sub-model

2.1.1 Direct-beam radiation

The direct-beam component of solar radiation (the radiation arriving directly from the sun) normal to a horizontal plate at the earth's surface, under clear sky and natural (without anthropogenic influence) atmosphere, is the extra-terrestrial radiation at the top of the atmosphere (TOA) modified by absorption and scattering from its various constituents. Thus, during cloudless periods, the direct-beam radiation received on a horizontal surface can be expressed as:

$$I_b = I_{ex} \cos\theta_z \, T_w \, T_r \, T_o \, T_{mg} \, T_a \tag{1}$$

where θ_z is the solar zenith angle, I_{ex} is the normal-incidence extra-terrestrial solar radiation in the n_i-th day of the year; the T terms are the broadband transmission functions for water vapor (T_w), Rayleigh scattering (T_r), uniformly mixed gases (CO_2, CO, N_2O, CH_4 and O_2) absorption (T_{mg}), ozone absorption (T_o), and aerosol total extinction (scattering & absorption) (T_a).

The general transmittance function, T_i, for seven main atmospheric gases (H_2O, O_3, CO_2, CO, N_2O, CH_4 and O_2) can be expressed by the following equation (Psiloglou et al., 1994, 1995a, 1996, 2000):

$$T_i = 1 - \frac{a \; m \; u_i}{(1 + b \; m \; u_i)^c + d \; m \; u_i} \tag{2}$$

where m is the relative optical air mass, and a, b, c, d are numerical coefficients that depend on the specific extinction process; the values of these coefficients are given in Table 1.

The relative optical air mass, m, at standard pressure conditions, is given by Kasten and Young (1989):

$$m = [\cos\theta_z + 0.50572\,(96.07995 - \theta_z)^{-1.6364}]^{-1} \tag{3}$$

This above formula is accurate for all m's up to $\theta_z < 85^\circ$ with an error of less than 0.5%. The absolute air mass, m', can then be estimated by the expression:

$$m' = m\left(\frac{P}{P_o}\right) \tag{4}$$

where P is the atmospheric pressure at the station's height, in hPa, and P_o=1013.25 hPa the mean pressure at sea level.

The relative optical air mass has been used here only for ozone, water vapor and aerosols, whereas the absolute air mass is used for the Rayleigh scattering and mixed gases absorption.

In Eq. (2), u_i represents the "absorber's amount in a vertical column" for each extinction process. This quantity is variable for water vapor and ozone, and represented by u_w (in cm) and u_o (in atm-cm), respectively. The necessary u_i values (in atm-cm) for the other atmospheric gases of Table 1 are: 1.60 for CH_4, 0.075 for CO, 330.0 for CO_2, 0.28 for N_2O, and 2.095×10^5 for O_2.

For the estimation of the water-vapor total amount in a vertical column (the so-called precipitable water), the following expression (Leckner, 1978) is used:

$$u_w = \frac{0.493\ e_m}{T} \tag{5}$$

where e_m is the partial water-vapor pressure, in hPa, given by:

$$e_m = e_s\left(\frac{\mathrm{RH}}{100}\right) \tag{6}$$

where RH is the relative humidity at the station's height, in %, and e_s is the saturation vapor pressure, in hPa, given by Gueymard (1993b):

$$e_s = \exp\left(22.329699 - 49.140396 T_1^{-1} - 10.921853 T_1^{-2} - 0.39015156 T_1\right) \tag{7}$$

with $T_1 = T/100$, T being the air temperature at the station's height, in K.

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

The broadband transmittance function due to the total absorption by the uniformly mixed gases can then be calculated by:

$$T_{mg} = T_{CO_2}\, T_{CO}\, T_{N_2O}\, T_{CH_4}\, T_{O_2} \tag{8}$$

where the transmittances T_{CO_2}, T_{CO}, T_{N_2O}, T_{CH_4} and T_{O_2} are given by Eq. (2) using the appropriate coefficients of Table 1.

The transmittance corresponding to the Rayleigh scattering is calculated from Psiloglou et al. (1995b):

$$T_r = \exp[-0.1128 m'^{0.8346}(0.9341 - m'^{0.9868} + 0.9391 m')] \tag{9}$$

Very few locations in the world provide detailed aerosol data. In general, solar radiation modelers are forced to use or develop aerosol models specific for their own site of application. In the present study, the Mie scattering transmittance function proposed by Yang et al. (2001) has been incorporated in MRM v5:

$$T_a = \exp\{-m\,\beta[0.6777 + 0.1464\, m\,\beta - 0.00626\, (m\,\beta)^2]^{-1.3}\} \tag{10}$$

where the Ångström's turbidity parameter, β, is in the range 0.05–0.4 for low-to-high aerosol loads. Some indicative values of β are given in Table 2 (Iqbal, 1983).

Another way of estimating β, when this is not known from measurements, is by using Yang et al.'s (2001) expression, which relates β to the geographical latitude, ϕ, and the altitude of the station, H. This expression is:

$$\beta = \beta' + \Delta\beta \tag{11}$$

$$\beta' = (0.025 + 0.1\ \cos\varphi)\ \ \exp\left(\frac{-0.7H}{1000}\right) \tag{12}$$

$$\Delta\beta = \pm(0.02 \sim 0.06) \tag{13}$$

where β' represents the annual mean value of turbidity and $\Delta\beta$ their seasonal deviations from the average, i.e. low values in winter, high values in the summer. For Athens

(ϕ=37.967° N, H=107 m a.m.s.l.) β'=0.09. Considering $\Delta\beta$=−0.04, it is found that β=0.05. This value was adopted for both days, since similar atmospheric conditions prevailed on 28 and 29 March, namely unaltered wind speeds and wind directions from the southern sector mostly.

During the earth's movement around the sun, I_{ex} varies by approximately ±3.5 percent of its value at the equinoxes. I_{ex} may be expressed in the n_i-th day of the year as (Spencer, 1971):

$$I_{ex} = I_o\,[1.00011 + 0.034221\ \cos\ \Gamma + 0.00128\ \sin\ \Gamma + 0.000719 \cos\ 2\Gamma + 0.000077 \sin\ 2\Gamma] \tag{14}$$

where I_o is the solar constant, equal to 1366.1 Wm^{-2}, and Γ (in radians) is the day angle, which is given by:

$$\Gamma = \frac{2\,\pi\ (n_i - 1\,)}{365} \tag{15}$$

where the day number of the year, n_i, ranges from 1 (on 1 January) to 365 (on 31 December); February is always assumed to have 28 days.

Figures 1–3 show the transmittances of water vapor, ozone and total aerosol extinction, respectively, as predicted by the new MRM v5 algorithm.

2.1.2 Diffuse radiation

Under clear-sky conditions, the diffuse (indirect) sky radiation is assumed to be made up of a portion of singly scattered by the atmospheric constituents (molecules and aerosol particles) direct-beam radiation, I_{ds}, plus a multiple-scattering component, I_{dm} (Atwater and Brown, 1974; Psiloglou et al., 2000):

$$I_{ds} = I_{ex} \cos\theta_z\, T_w\, T_{mg}\, T_o\, T_{aa}\, 0.5(1 - T_{as}\, T_r) \tag{16}$$

The first part in the right-hand side of Eq. (16), i.e. $I_{ex}\, T_w\, T_{mg}\, T_o\, T_{aa}$, represents the amount of solar radiation left over after its absorption by the atmospheric constituents and aerosols, while the second part, i.e. $0.5(1-T_{as}T_r)$, expresses the amount of solar radiation scattered forward (towards the surface of the earth) by the air molecules and aerosol particles.

The aerosol transmittance function due to absorption only, T_{aa}, is given by the expression (Bird and Hulstrom, 1980, 1981):

$$T_{aa} = 1 - 0.1(1 - m + m^{1.06})(1 - T_a) \tag{17}$$

and the aerosol transmittance due to scattering alone, T_{as}, can be estimated from:

$$T_{as} = \frac{T_a}{T_{aa}} \tag{18}$$

The diffuse component which is due to a single reflection of I_b and I_{ds} from the earth's surface, followed by backscattering from the atmospheric constituents, I_{dm}, is modeled as:

$$I_{dm} = (I_b + I_{ds}) \frac{\alpha_g \alpha_s}{1 - \alpha_g \alpha_s} \tag{19}$$

where α_g is the surface albedo, usually taken equal to 0.2, and α_s the albedo of the cloudless sky.

The atmospheric albedo is defined as the ratio of the energy reflected back to space to the incident one. Under clear-sky conditions, it can be approximated using the following form:

$$\alpha_s = \alpha_r + \alpha_a \tag{20}$$

where α_r represents the albedo due to molecular (Rayleigh) scattering, commonly taken equal to 0.0685 after Lacis and Hansen (1974).

The second term, α_a, is the atmospheric aerosol albedo due to atmospheric aerosol scattering, and can be estimated from the following equation (Bird and Hulstrom, 1980, 1981):

$$\alpha_a = 0.16(1 - T_{a,1.66}) \tag{21}$$

where $T_{a,1.66}$ implies the value of the total aerosol transmittance, T_a, calculated for m=1.66 (i.e., for θ_z=53°).

The diffuse radiation at ground level under clear-sky conditions, I_d, is then simply the sum of the I_{ds} and I_{dm} components, i.e.:

$$I_d = I_{ds} + I_{dm} \tag{22}$$

2.1.3 Total radiation

The total solar radiation, I_t, received under clear-sky conditions on a horizontal surface at the surface of the earth is simply the sum of the horizontal components of I_b from Eq. (1), and I_d from Eq. (22):

$$I_t = I_b + I_d = \frac{I_b + I_{ds}}{1 - \alpha_g\, \alpha_s} \tag{23}$$

2.2 Cloudy-sky MRM sub-model

Clouds play an important role in modifying radiation as they significantly affect the reflectance, absorptance and transmittance of the incident radiation. However, the present understanding of their effect on solar radiation is at a good level, but its modeling in the various radiative models (broadband or spectral) is far from being efficient and lies on statistical techniques than physical processes (Kontratyev, 1969; Davies et al., 1975; Suckling and Hay, 1977; Barbaro et al., 1979; Munro, 1991; Gu et al., 2001; Badescu, 2002; Ehnberg and Bollen, 2005).

The direct-beam radiation is attenuated by the presence of clouds by blocking its propagation through the atmosphere, as well as by the various atmospheric constituents, as already discussed above. The depletion of the direct-beam component by clouds depends on their type, thickness, and the number of layers.

The diffuse component consists of several parts. The mechanism of scattering by air molecules and aerosols is the same with the one already described above. In addition,

ACPD
7, 12807–12843, 2007

EGU

there is an interaction between the direct-beam solar radiation with clouds, resulting in reflected diffuse radiation. Further, a portion of the direct-beam and diffuse radiation components reaching the surface of the earth is reflected back to space; this part contributes to a multiply-reflected irradiance. This latter radiation component depends strongly on the reflectance properties of the clouds system. When the sky is completely overcast, the diffuse component is considered almost isotropic.

Theoretical determinations of the direct-beam and diffuse irradiance components under cloudy-sky conditions are quite difficult. Such tasks require detailed data on the type and optical properties of clouds, cloud coverage, thickness, position and number of layers. Such data are very rarely collected on a routine basis.

However, several methods have been developed to model solar radiation under cloudy skies. Depending on the type of input data used for each model, Davies et al. (1984) identified five model groups: (i) sunshine-based models, (ii) cloud-layer-based models, (iii) total-cloud-based models, (iv) satellite-data-based models, and (v) Liu-Jordan (1960) type models; all these groups discriminate total radiation into direct-beam and diffuse components.

In the last version of MRM, an algorithm for calculating the solar radiation components on cloudy days has been introduced. Given the absence of adequate information on cloudiness, solar radiation is simulated by MRM using the measured sunshine duration, n, which is widely measured and easily available to most users from existing national meteorological stations.

2.2.1 Direct-beam radiation

The direct-beam solar radiation under clear skies, I_b, decreases in the presence of clouds by the factor T_c, which depends on the characteristics of cloudiness (Barbaro et al., 1979). Therefore, the direct-beam solar radiation under cloudy skies, I_{cb}, can be obtained by:

$$I_{cb} = I_b \, T_c \tag{24}$$

where T_c is the cloud transmittance, and I_b is calculated from Eq. (1).

Generally, T_c can be expressed as a function of the relative sunshine duration, n/N, which is the ratio of the daily measured sunshine duration, n, to its maximum (astronomical) value, N:

$$T_c = k \left(\frac{n}{N}\right) \tag{25}$$

where k is an empirical coefficient for cloudiness with a usual value equal to unity. Such an approximation, as that in Eq. (24), is necessary because the information pertaining to cloudiness is unsatisfactory.

Barbaro (1979) allows k=1, but Ideriah (1981) proposed a value of k=0.75 to provide better agreement between modeled estimates and measurements. For the Athens data it was found that k should vary between 0.85 and 0.95 for the winter months, and be 1.0 for the summer period (Psiloglou et al., 2000).

2.2.2 Diffuse radiation

The single-scattered portion of the diffuse radiation in the presence of clouds, T_{cds}, can be computed by Barbaro et al. (1979):

$$I_{cds} = I_{ds}T_c + k^*(1 - T_c)(I_b + I_{ds}) \tag{26}$$

where k^* is an empirical transmission coefficient, whose value is a function of ϕ, and is obtained from Berland and Danilchenko (1961). Values of k^* for different latitudes are given in Table 3. For the case of Athens (ϕ=38° N), the value of k^*=0.33 has been adopted (see Table 3).

The ground-reflected, atmospheric- and cloud-backscattered diffuse term, I_{cdm}, is modeled identically as in clear-sky conditions:

$$I_{cdm} = (I_{cb} + I_{cds})\ \frac{\alpha_g\ \alpha_{cs}}{1 - \alpha_g\ \alpha_{cs}} \tag{27}$$

where α_{cs} is the albedo of the cloudy sky.

In order to estimate the atmospheric albedo of a cloudy sky, a corrective factor for multiple scattering between the clouds and the surface of the earth, α_c, is introduced in Eq. (20). Thus the new formula is expressed as:

$$\alpha_{cs} = \alpha_r + \alpha_a + \alpha_c \tag{28}$$

where the α's in the right-hand side of Eq. (28) are defined for clear skies (see Eqs. 20, 21), while α_c is given by various analytical expressions (Atwater and Ball, 1978; Davies and McKay, 1982; Lyons and Edwards, 1982), as a function of n. In MRM v5, the following expression has been adopted:

$$\alpha_c = v\left(1 - \frac{n}{N}\right) \tag{29}$$

where v is a parameter varying between 0.3 and 0.6. For Athens, the value of v=0.4 was found to be more appropriate (Psiloglou et al., 2000).

Therefore, the diffuse radiation at ground level under cloudy skies, I_{cd}, is the sum of the I_{cds} and I_{cdm} components, i.e.:

$$I_{cd} = I_{cds} + I_{cdm} \tag{30}$$

2.2.3 Total radiation

The total solar radiation received under cloudy-sky (partly or overcast) conditions on horizontal surface is again the sum of the horizontal direct-beam and diffuse components, i.e.:

$$I_{ct} = I_{cb} + I_{cd} = \frac{I_{cb} + I_{cds}}{1 - \alpha_g \alpha_{cs}} \tag{31}$$

ACPD
7, 12807–12843, 2007

3 Validation of MRM v5

3.1 Data collection and quality test

In order to evaluate the performance of the newly introduced version 5 of the MRM algorithm under normal and extraordinary conditions, 1-min mean total and diffuse horizontal solar irradiance data (Wm^{-2}) from the Actinometric Station of NOA (ASNOA) were used together with concurrent values of dry-bulb temperature, relative humidity, sunshine duration, and atmospheric pressure at the station's height from the meteorological station of NOA, for 28 (typical clear day) and 29 (eclipse day) March 2006.

NOA (latitude 37.967° N, longitude 23.717° E) is located on a small hill with elevation of 107 m a.m.s.l., near the center of Athens. The Athens Metropolitan area is located in the central part of the Attika Peninsula in an oblong basin having a NE-SW direction; the basin has an area of 450 km^2 and is inhabited by 3.5 millions of people (census of 2001). To the east of the basin's axis, the city is less densely populated. To the west, the area is $\frac{3}{4}$ industrial and $\frac{1}{4}$ residential. The average annual sunshine duration is 2919 h.

The actinometers for measuring the total and diffuse horizontal radiation measurements at ASNOA are Eppley PSP pyranometers; in addition, the diffuse radiation is measured by using a shadow ring over the pyranometer.

To establish a valid set of measurements for the validation of the MRM code, the 1-min mean total and diffuse horizontal irradiance values were thoroughly tested for errors. A routine quality-control procedure was applied; erroneous data were excluded. The quality tests screened out all (i) diffuse horizontal values greater than 110% of the corresponding total horizontal ones; (ii) total horizontal values greater than 120% of the seasonally correct solar constant; (iii) diffuse horizontal values greater than 80% of the seasonally correct solar constant; (iv) total horizontal values equal to or less than 5 Wm^{-2}, during sunrise and sunset, due to the pyranometers' sensitivity; (v) data for a solar altitude less than 5 degrees; and (vi) data with the direct-beam solar component exceeding the extraterrestrial solar irradiance. It must be noted here that on the eclipse

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

day and during the phenomenon, from its start to its end, I_{ex} was multiplied by the factor 1-EM, where EM is the eclipse magnitude, i.e. the fraction of the solar disk covered by the moon's shadow. This was done in order to simulate the phenomenon in the MRM algorithm.

The value of u_o in the MRM can either be calculated through the Van Heuklon (1979) methodology or be given in atm-cm from available satellite or ground-based instruments. In the present study, the value of u_o was obtained from a Brewer spectrophotometer operating in the center of Athens (Academy of Athens). No matter which of the above mentioned methodologies is used, the u_o value is introduced in the MRM as an average daily value. These average daily values were 279.8 and 316.9 DU (1 atm-cm=1 DU$\times 10^{-3}$) for 28 and 29 March 2006, respectively.

The calculations of the solar position in the sky on both dates (prior and during the eclipse) were performed using the modified SUNAE algorithm (Walraven, 1978), incorporating all corrections introduced by Wilkinson (1981), Muir (1983), Kambezidis and Papanikolaou (1990b), and Kambezidis and Tsangrassoulis (1993b).

Table 4 gives the 1-min values of EM during the eclipse day. The start of the eclipse is taken at 0 min (11:30 h LST) in the left column of the Table corresponding to the last minute before the beginning of the sun's disk blockage by the moon. The maximum of the eclipse was for Athens 84% at 12:48 h LST. The descending limb of the phenomenon lasted 77 min and the whole phenomenon 154 min, i.e. from 11:30 h LST to 14:04 h LST.

3.2 Statistical analysis

The Root Mean Square Error (RMSE) and the Mean Bias Error (MBE), expressed as the percentage of the measured mean value, were used as indicators of the model's performance:

$$\mathrm{RMSE}\,(\%) = \frac{\sqrt{\sum_{i=1}^{M} (I_m - I_c)^2 \Big/ M}}{\sum_{i=1}^{M} I_m \Big/ M} \times 100 \tag{32}$$

$$\mathrm{MBE}\,(\%) = \frac{\sum_{i=1}^{M} (I_m - I_c) \Big/ M}{\sum_{i=1}^{M} I_m \Big/ M} \times 100 \tag{33}$$

where I_m and I_c are the measured and model-estimated values of the total or diffuse radiation and M is the number of data points on one day before (28 March, 2006) or the day of the eclipse (29 March, 2006). The values of these estimators for 28 and 29 March 2006 are given in Table 5.

The comparison between the MRM-modeled radiation components (total and diffuse) and the measured ones for the day before the eclipse is shown in Fig. 4. A very good agreement is observed, an observation that is also obvious from the statistical estimators in Table 5.

Figure 5 shows the same comparison as Fig. 4 does, but for the eclipse day. The performance of MRM v5 seems to be excellent, a fact that is also confirmed by the RMSE and MBE statistics of Table 5. Both statistical estimators concerning the total horizontal irradiance are very good even compared to those of the previous day. There must be noted here that 28 March was an almost cloudless day, while on the eclipse day some cloudiness was developed over Athens after the start of the phenomenon. This is the reason for increased values in both statistical estimators in the diffuse radiation component. To the contrary, the RMSE and MBE obtain very satisfactory values for the total horizontal irradiance even compared with those on a typical cloudless day, such as 28 March 2006. Such a harsh test (eclipse with cloudy sky) for a broadband radiation model constitutes an ultimate validation of its performance. Therefore, the excellent performance of MRM v5 has been affirmed by the close agreement of the modeled and measured radiation components under adverse conditions.

To further show the capabilities of the MRM, Fig. 6 is drawn. The left panel of the figure refers to the one-to-one comparison between the estimated and measured total horizontal irradiances on 28 March and the right panel refers to the 29 March case. It is easily seen that in both cases the data points are along the $y=x$ line and without great dispersion around it.

4 Conclusions

This study dealt with the validation of the Meteorological Radiation Model (MRM) developed by the Atmospheric Research Team of the National Observatory of Athens. Though the model, in its previous versions, has been tested in the past against measurements, this was the first time that the performance of the latest version 5 of the MRM algorithm was tested. To do this, a difficult case, such as the solar eclipse of 29 March 2006 over Athens with cloudy sky, was chosen.

The test proved that the MRM v5 is an efficient broadband code capable in simulating solar irradiance at a location not only under clear-sky conditions, but also with cloudy weather. Moreover, the mix of such sky conditions with an eclipse event is done for the first time in the international literature as far as a solar broadband model is concerned. The results showed that the MRM simulated the solar radiation levels changes during the almost total solar eclipse of 29 March 2006 over Athens very well. Indeed, the RMSE and MBE statistical estimators were 7.64% and −1.67% on 29 March for the simulated total solar radiation in comparison with the respective 5.30% and +2.04% for the previous clear day.

The efficiency of the MRM constitutes the model capable in handling other simulation situations as easily as in the case of a solar eclipse with even better results.

ACPD
7, 12807–12843, 2007

Therefore, the MRM can be used in a variety of applications, among which there can be atmospheric physics, photovoltaic studies, complement of missing data from a solar radiation time series, solar thermal projects, agricultural studies, architectural designs. The MRM can also be used in the derivation of a Solar Radiation (or Energy) Atlas over a region with as much accuracy as possible. This latter applicability makes MRM a precious tool in the energy sector.

Appendix A

Symbol List

a, b, c, d	numerical coefficients in the general transmittance function of various atmospheric constituents
α_a	atmospheric aerosol albedo due to atmospheric aerosol scattering
α_c	corrective factor for multiple scattering between the clouds and the surface of a cloudy sky
α_{cs}	atmospheric albedo of a cloudy sky
α_g	surface albedo
α_r	atmospheric albedo due to molecular (Rayleigh) scattering
α_s	atmospheric albedo of a cloudless sky
e_m	partial water-vapor pressure, in hPa
e_s	saturation vapor pressure, in hPa
H	station's altitude, in meters
I_{ex}	normal-incidence extra-terrestrial solar radiation in the n_i-th day of the year
I_c	model-estimated value of total or diffuse solar radiation, for RMSE or MBE statistical indicators estimation
I_b	direct-beam component of solar radiation, normal to a horizontal plate at the earth's surface, under clear sky conditions
I_{cb}	direct-beam component of solar radiation, normal to a horizontal plate at the earth's surface, under cloudy-sky conditions
I_{cd}	diffuse component of solar radiation, normal to a horizontal plate at the earth's surface, under cloudy-sky conditions
I_{cdm}	ground-reflected, atmospheric- and cloud-backscatttered portion of the diffuse sky radiation under cloudy-sky conditions

ACPD

7, 12807–12843, 2007

I_{cds} portion of the diffuse sky radiation under cloudy-sky conditions, singly scattered by the atmospheric constituents (molecules and aerosol particles)

I_{ct} total solar radiation, normal to a horizontal plate at the earth's surface, under cloudy-sky conditions

I_d diffuse component of solar radiation, normal to a horizontal plate at the earth's surface, under clear sky conditions

I_{dm} ground-reflected, atmospheric-backscatttered portion of the diffuse sky radiation under clear sky conditions

I_{ds} portion of the diffuse sky radiation under clear sky conditions, singly scattered by the atmospheric constituents (molecules and aerosol particles)

I_m measured value of total or diffuse solar radiation, for RMSE or MBE statistical indicators estimation

I_o the solar constant, equal to 1366.1 Wm^{-2}

I_t total solar radiation, normal to a horizontal plate at the earth's surface, under clear sky conditions

k empirical coefficient for cloudiness

k^* empirical transmission coefficient for the single-scattered portion of the diffuse radiation under cloudy-sky conditions

m relative optical air mass

m' absolute optical air mass

M number of available data points of total or diffuse solar radiation, for the RMSE or MBE statistical indicators estimation

n daily measured sunshine duration, in hours

N daily maximum (astronomical) sunshine duration, in hours

n_i the day number of the year, ranges from 1 to 365

P atmospheric pressure at the station's height, in hPa

P_o mean pressure at sea level (equal to 1013.25 hPa)

RH relative humidity at the station's height, in %

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

T	air temperature at the station's height, in K
T_1	equal to $T/100$
T_a	broadband transmittance function for aerosol total extinction (scattering & absorption)
$T_{a,1.66}$	broadband transmittance function for aerosol total extinction, calculated for air mass m=1.66
T_{aa}	broadband aerosol transmittance function due to absorption only
T_{as}	broadband aerosol transmittance function due to scattering only
T_c	cloud transmittance
T_{CH_4}	broadband transmittance function for CH_4 absorption
T_{CO}	broadband transmittance function for CO absorption
T_{CO_2}	broadband transmittance function for CO_2 absorption
T_{mg}	broadband transmittance function due to total uniformly mixed gases' (CO_2, CO, N_2O, CH_4 and O_2) absorption
T_{N_2O}	broadband transmittance function for N_2O absorption
T_{O_2}	broadband transmittance function for O_2 absorption
T_o	broadband transmittance function for ozone absorption
T_r	broadband transmittance function for Rayleigh scattering
T_w	broadband transmittance function for water vapor absorption
u_o	total ozone amount in a vertical column, in atm-cm
u_i	total amount in a vertical column for atmospheric uniformly mixed gases, in atm-cm (i=CO_2, CO, N_2O, CH_4, O_2)
u_w	water-vapor total amount in a vertical column, in cm
V	horizontal visibility around the station

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

Greek letters

β	Ångström's turbidity parameter
β'	annual mean value of Ångström's turbidity parameter
$\Delta\beta$	seasonal deviations from the average of Ångström's turbidity parameter
Γ	day angle, in radians
θ_z	solar zenith angle, in degrees
ϕ	station's geographical latitude, in degrees

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ACPD
7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

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ACPD
7, 12807–12843, 2007

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ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

Table 1. Values of the coefficients *a*, *b*, *c* and *d* in the general transmittance function of Eq. (2) for various atmospheric constituents.

Atmospheric constituent	*a*	*b*	*c*	*d*
H_2O	3.0140	119.300	0.6440	5.8140
O_3	0.2554	6107.26	0.2040	0.4710
CO_2	0.7210	377.890	0.5855	3.1709
CO	0.0062	243.670	0.4246	1.7222
N_2O	0.0326	107.413	0.5501	0.9093
CH_4	0.0192	166.095	0.4221	0.7186
O_2	0.0003	476.934	0.4892	0.1261

ACPD

7, 12807–12843, 2007

Table 2. Indicative values of Ångström's turbidity parameter β for various atmospheric conditions and horizontal visibilities, V.

Atmospheric condition	β	V (km)
Clean	0.05	340
Clear	0.10	28
Turbid	0.20	11
Very turbid	0.40–0.50	<5

ACPD

7, 12807–12843, 2007

Table 3. Typical values of k^* as proposed by Berland and Danilchenko (1961) for different latitudes.

k^*	ϕ (degrees)
0.32	30
0.32	35
0.33	40
0.34	45

Table 4. Sun's disk coverage (EM) by the moon over Athens on 29 March 2006 from the start of the phenomenon until its maximum.

Time (min)	EM	Time (min)	EM	Time (min)	EM	Time (min)	EM
0	0.0000	20	0.1253	40	0.3411	60	0.6008
1	0.0015	21	0.1346	41	0.3533	61	0.6146
2	0.0041	22	0.144	42	0.3655	62	0.6283
3	0.0075	23	0.1537	43	0.3779	63	0.6422
4	0.0115	24	0.1635	44	0.3903	64	0.6560
5	0.0161	25	0.1736	45	0.4030	65	0.6700
6	0.0211	26	0.1837	46	0.4155	66	0.6839
7	0.0266	27	0.1941	47	0.4283	67	0.6980
8	0.0324	28	0.2045	48	0.4411	68	0.7120
9	0.0386	29	0.2152	49	0.4541	69	0.7261
10	0.0451	30	0.2259	50	0.4670	70	0.7402
11	0.0520	31	0.2369	51	0.4801	71	0.7544
12	0.0591	32	0.2479	52	0.4932	72	0.7686
13	0.0665	33	0.2592	53	0.5065	73	0.7828
14	0.0742	34	0.2705	54	0.5197	74	0.7970
15	0.0822	35	0.2820	55	0.5331	75	0.8114
16	0.0903	36	0.2936	56	0.5465	76	0.8256
17	0.0988	37	0.3053	57	0.5601	77	0.8400
18	0.1074	38	0.3171	58	0.5736		
19	0.1163	39	0.3291	59	0.5872		
continued	↑	continued	↑	continued	↑		

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

Table 5. RMSEs and MBEs for the MRM-modeled total and diffuse horizontal radiation components together with their mean measured values for 28 and 29 March 2006, at ASNOA.

March 2006	Mean diffuse rad. (Wm^{-2})	Mean total rad. (Wm^{-2})	RMSE (%)		MBE (%)	
			Diffuse	Total	Diffuse	Total
28	87.83	560.61	25.80	5.30	−2.50	+2.04
29	175.63	395.17	48.59	7.64	+35.53	−1.67

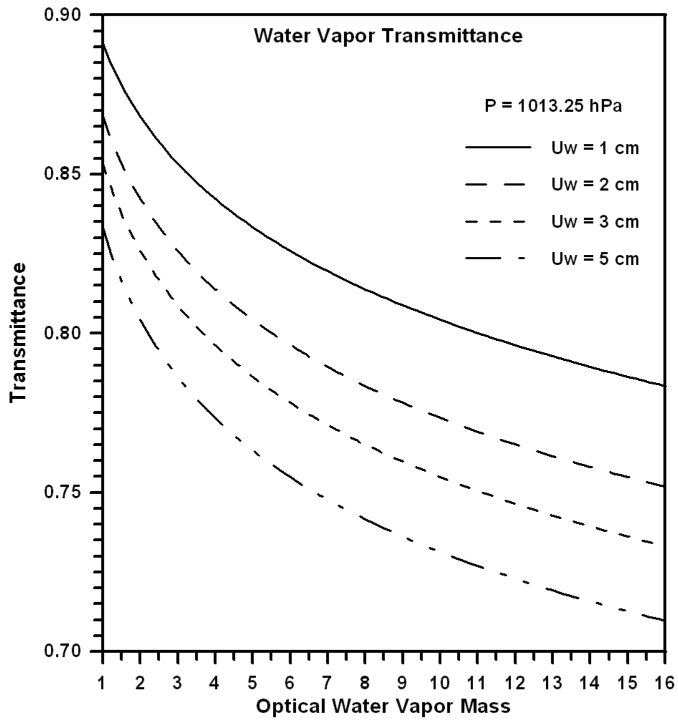

Fig. 1. Water-vapor absorption transmittance for different values of u_w, as predicted by MRM v5.

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

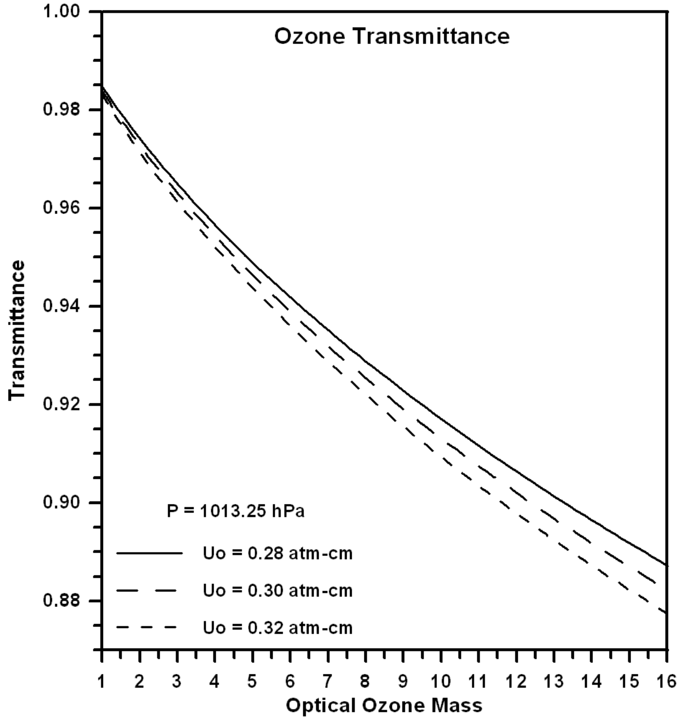

Fig. 2. Ozone absorption transmittance for different values of u_o, as predicted by MRM v5.

ACPD
7, 12807–12843, 2007

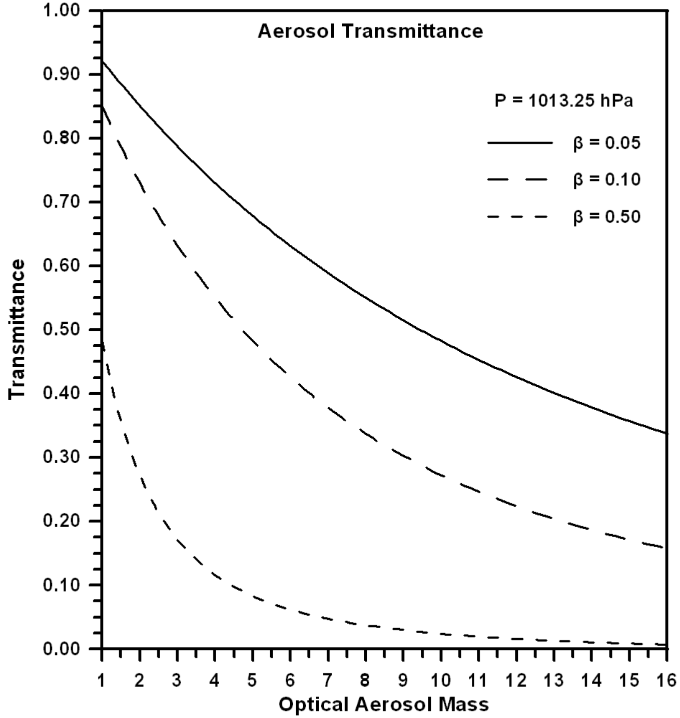

Fig. 3. Total aerosol extinction transmittance for different values of β, as predicted by MRM v5.

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

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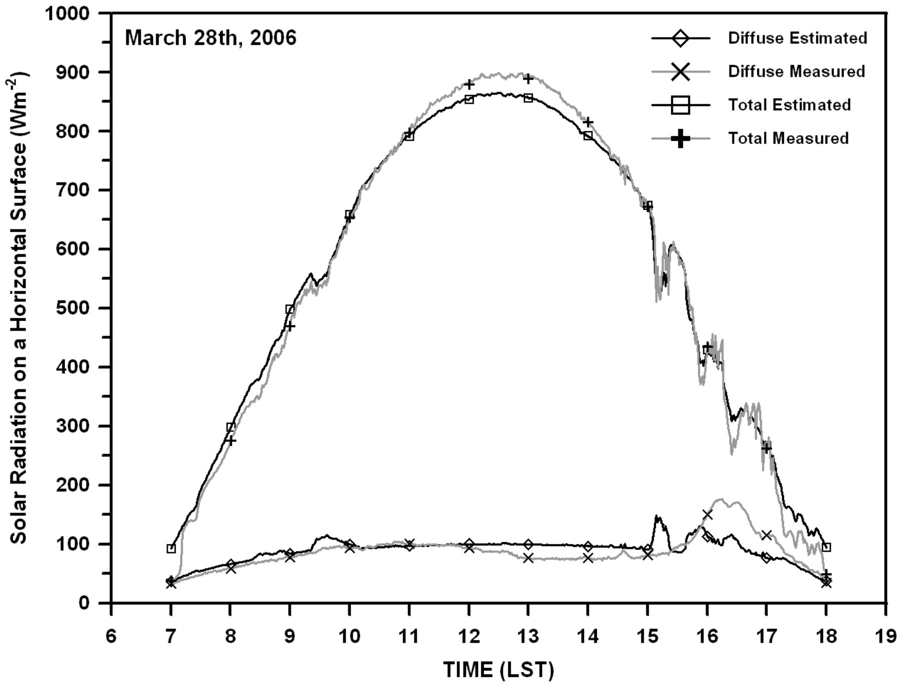

Fig. 4. Comparison between MRM simulations (black lines) and measurements (gray lines) for Athens on 28 March, 2006.

ACPD
7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU

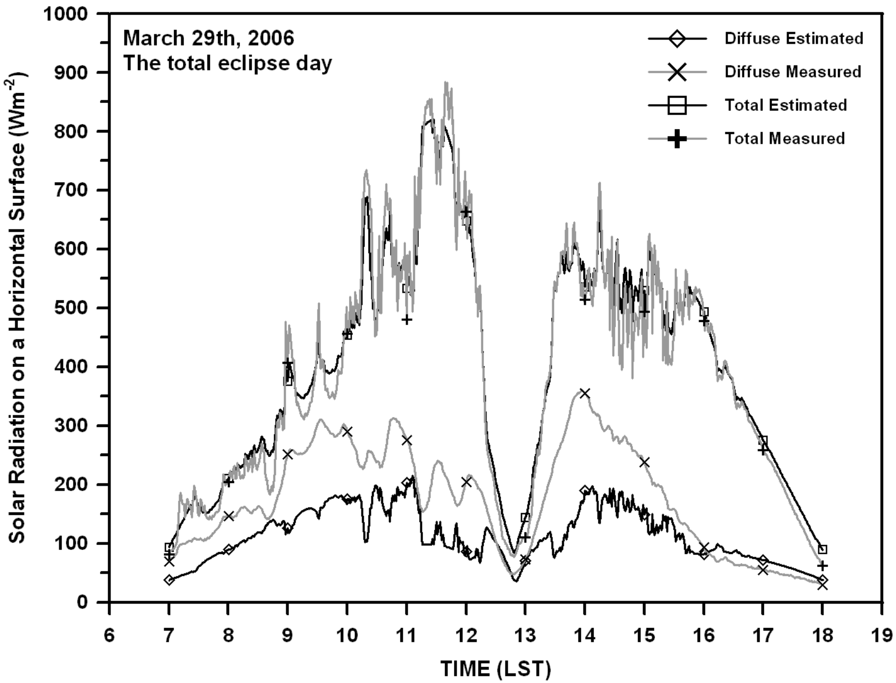

Fig. 5. Comparison between MRM simulations (black lines) and measurements (gray lines) for Athens on 29 March, 2006.

ACPD

7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

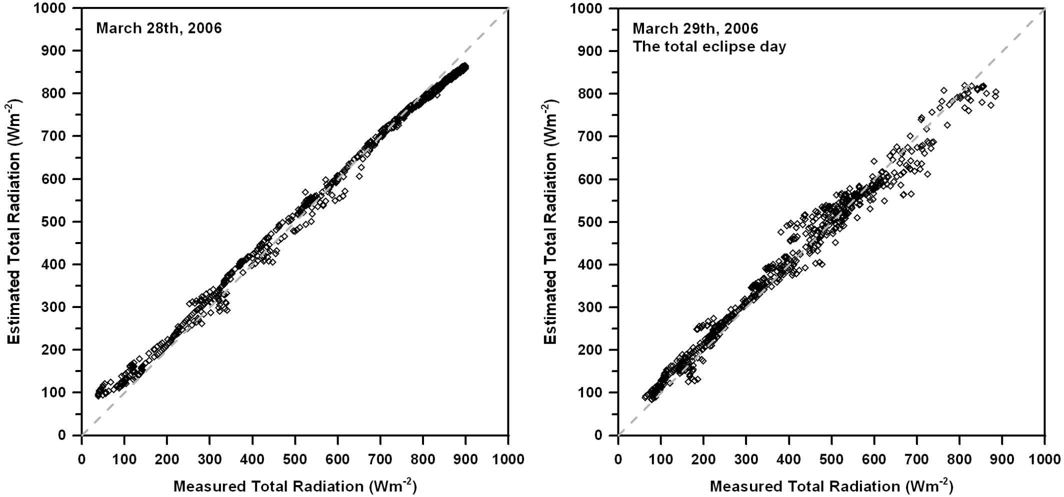

Fig. 6. Estimated vs. measured values of total solar radiation on horizontal surface for 28 (left) and 29 (right) March 2006. The $y=x$ (dashed) line shows, in general, the case of ideal agreement between estimated and measured values.

ACPD
7, 12807–12843, 2007

Performance of the MRM model during a solar eclipse

B. E. Psiloglou and H. D. Kambezidis

EGU